High Temperature Energy Storage Concepts

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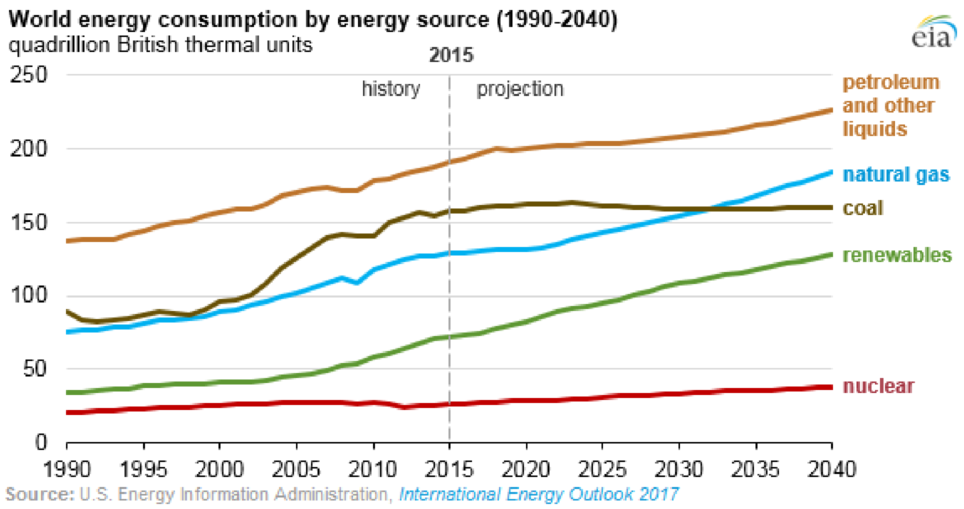
Outline

- Energy in the World
- Challenges on the Energy Path
- CSP Plants & Energy Storage
- Design concepts
- R&D Storage Materials
- Future Perspectives

A World of Energy

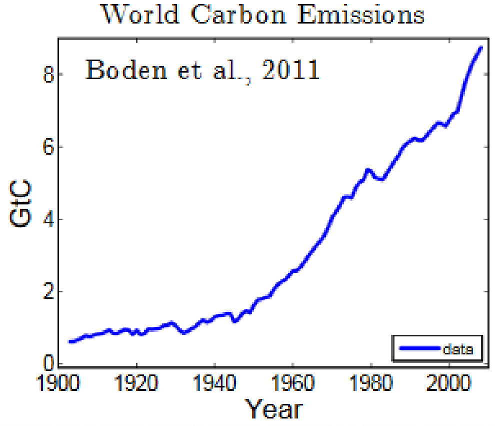


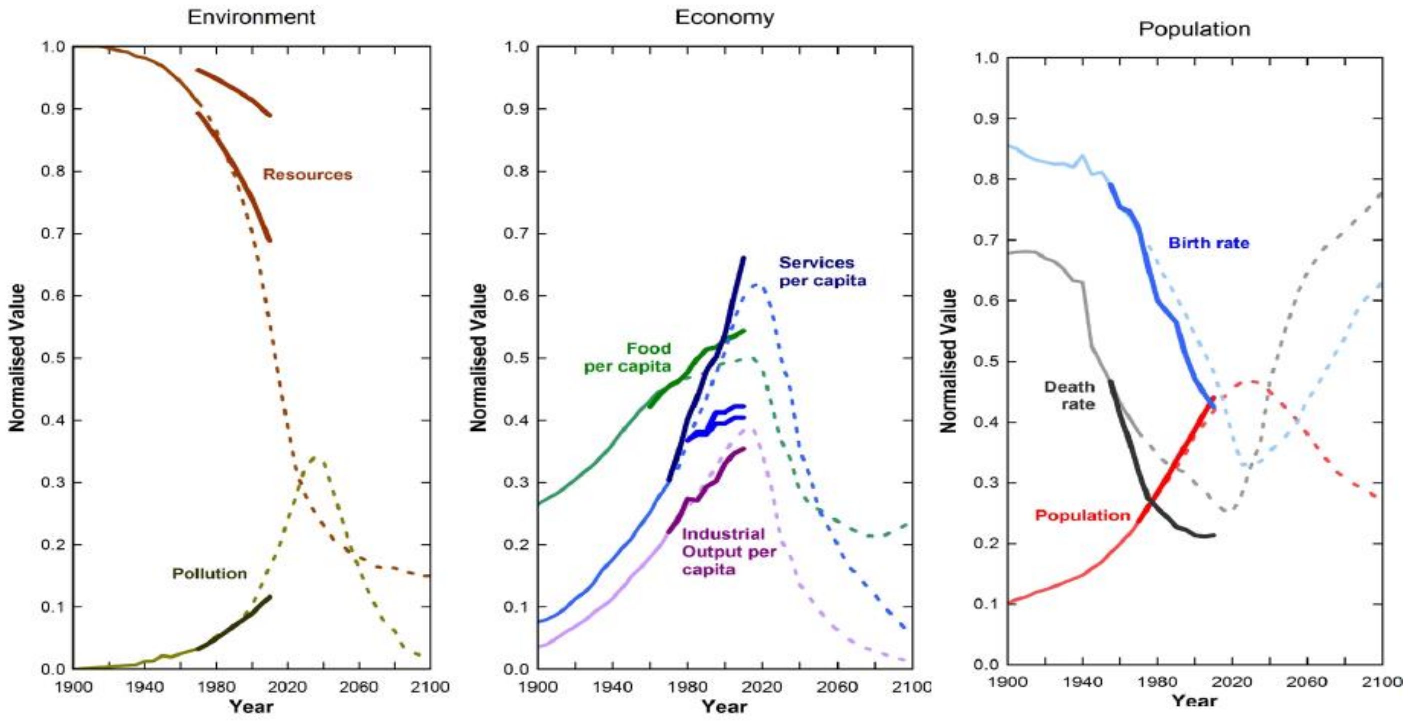
World Energy Consumption expected to increase 30% until 2040.

Except for coal, all other energy sources are expected to continue a growing trend.

World Model – LTG: Energy Transition

"*Energie Wende*" is a must





Source: LTG, Meadows

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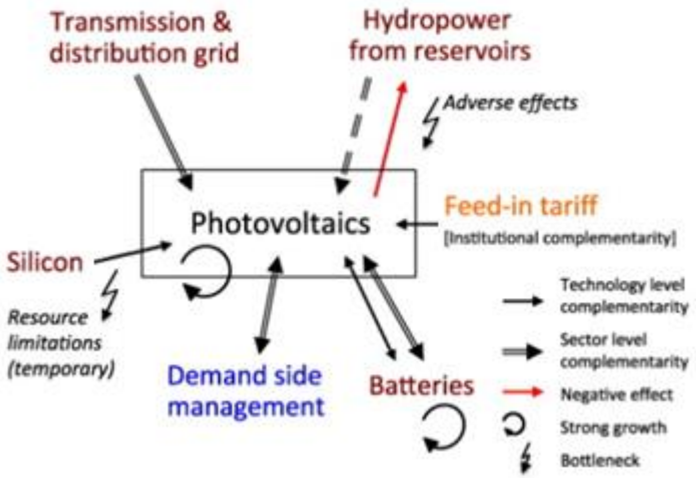
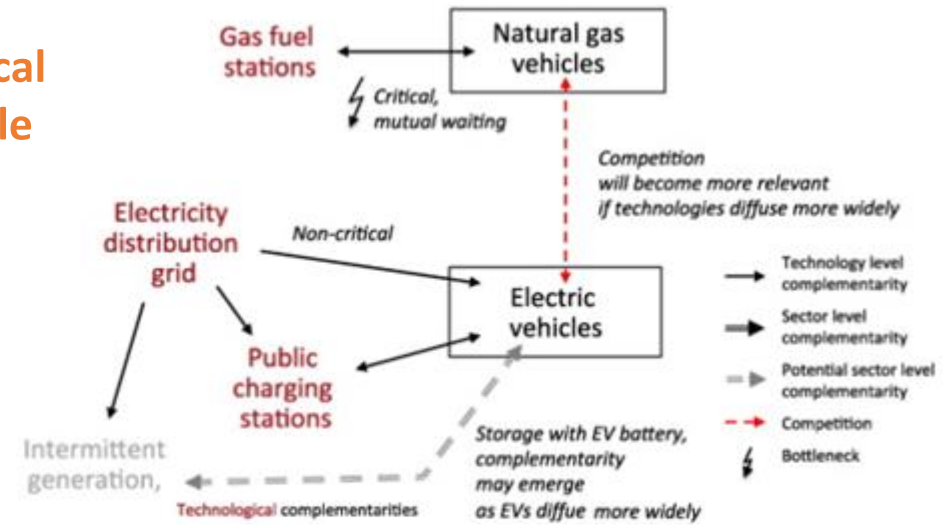
Clean Tech Path

PV

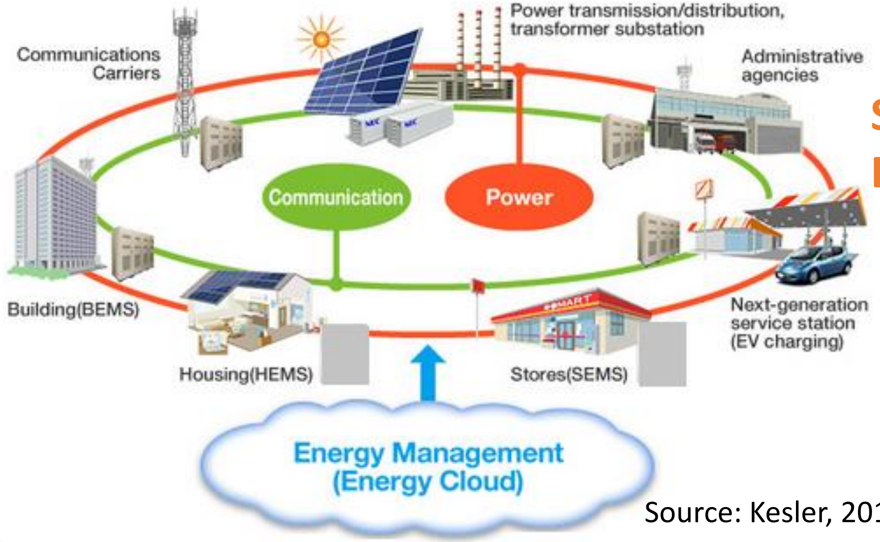


Electrical Vehicle



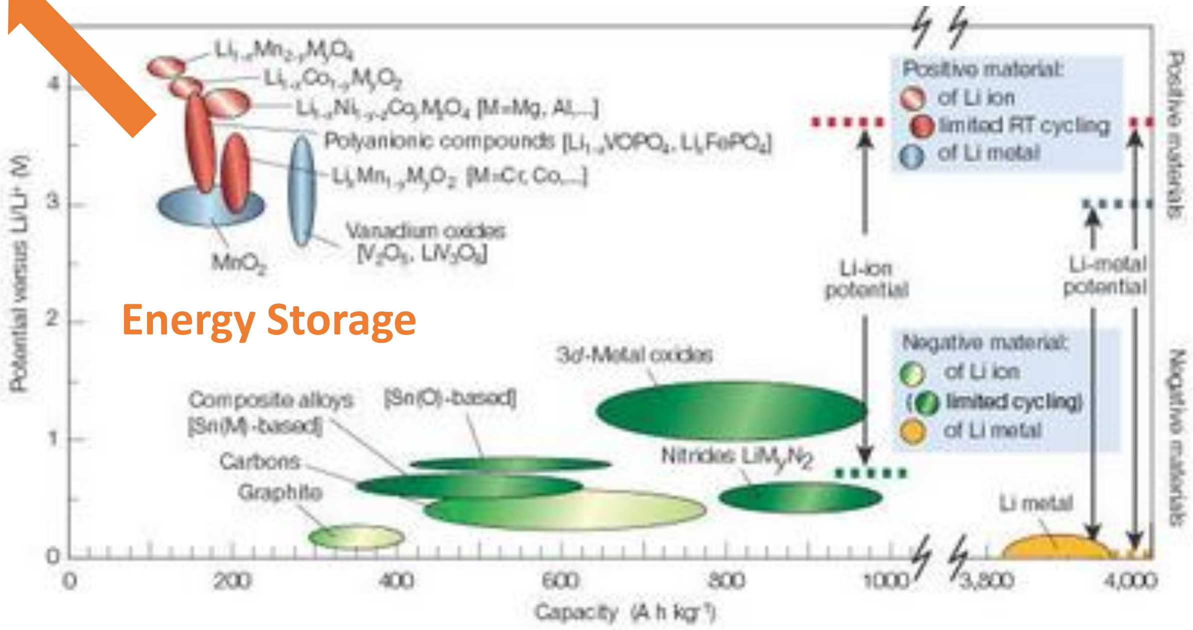
Societal changes

Smart Grid / Decentralization



Source: Kesler, 2016

Energy Storage



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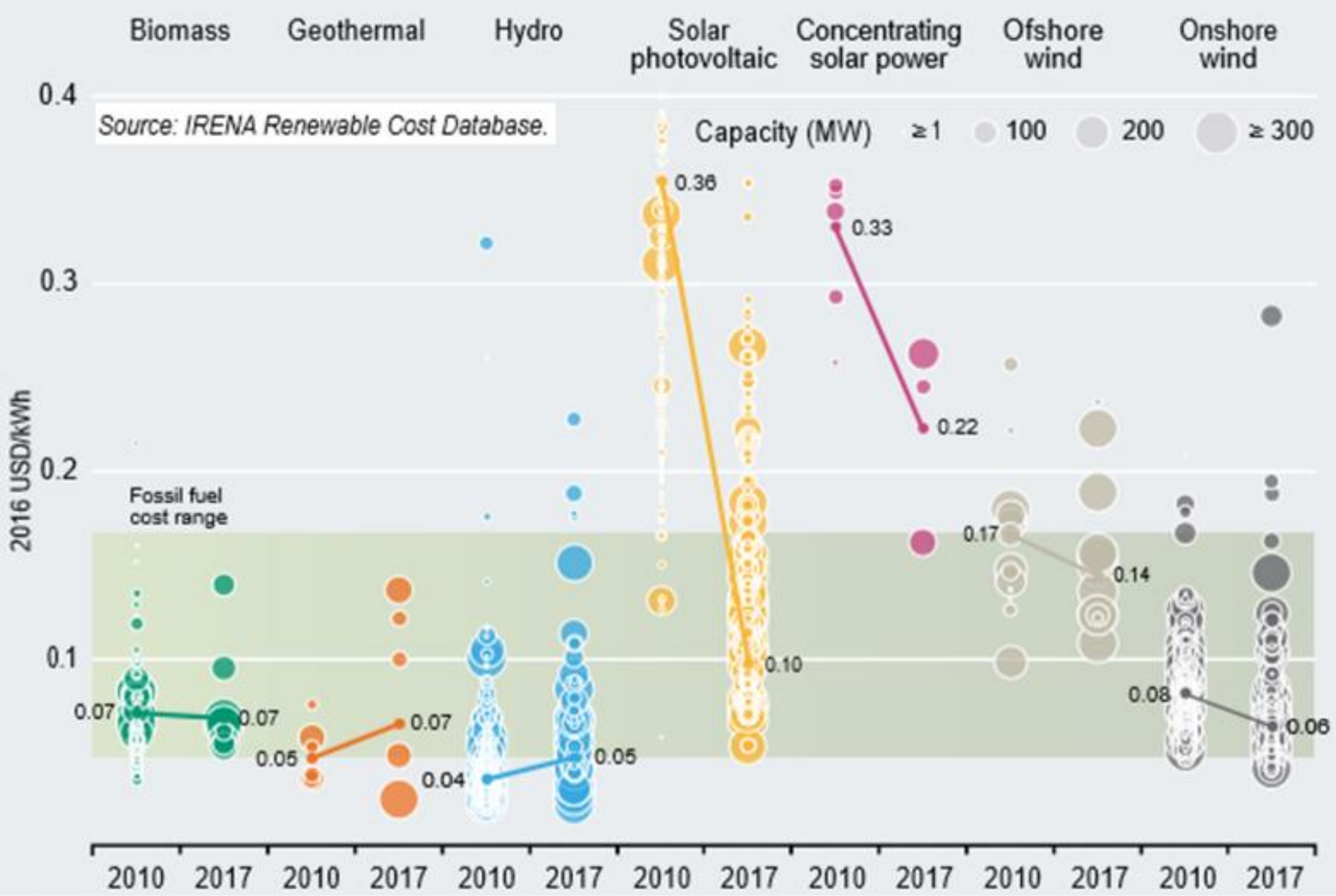
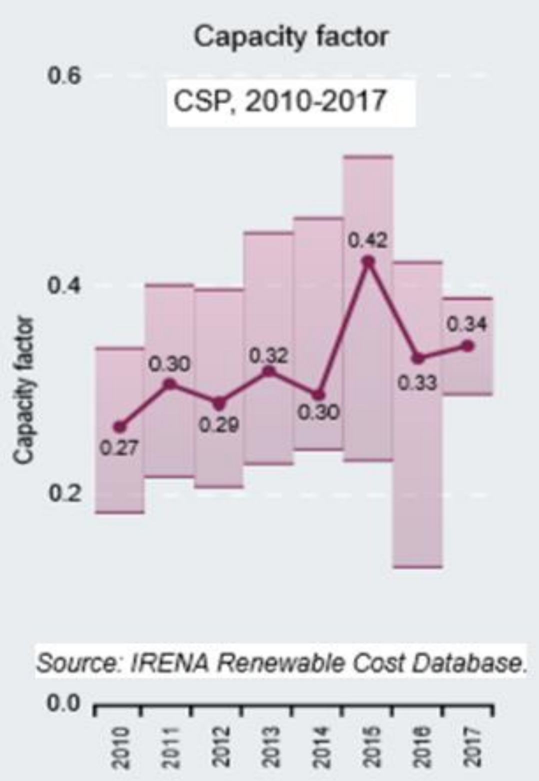
Clean Tech Path

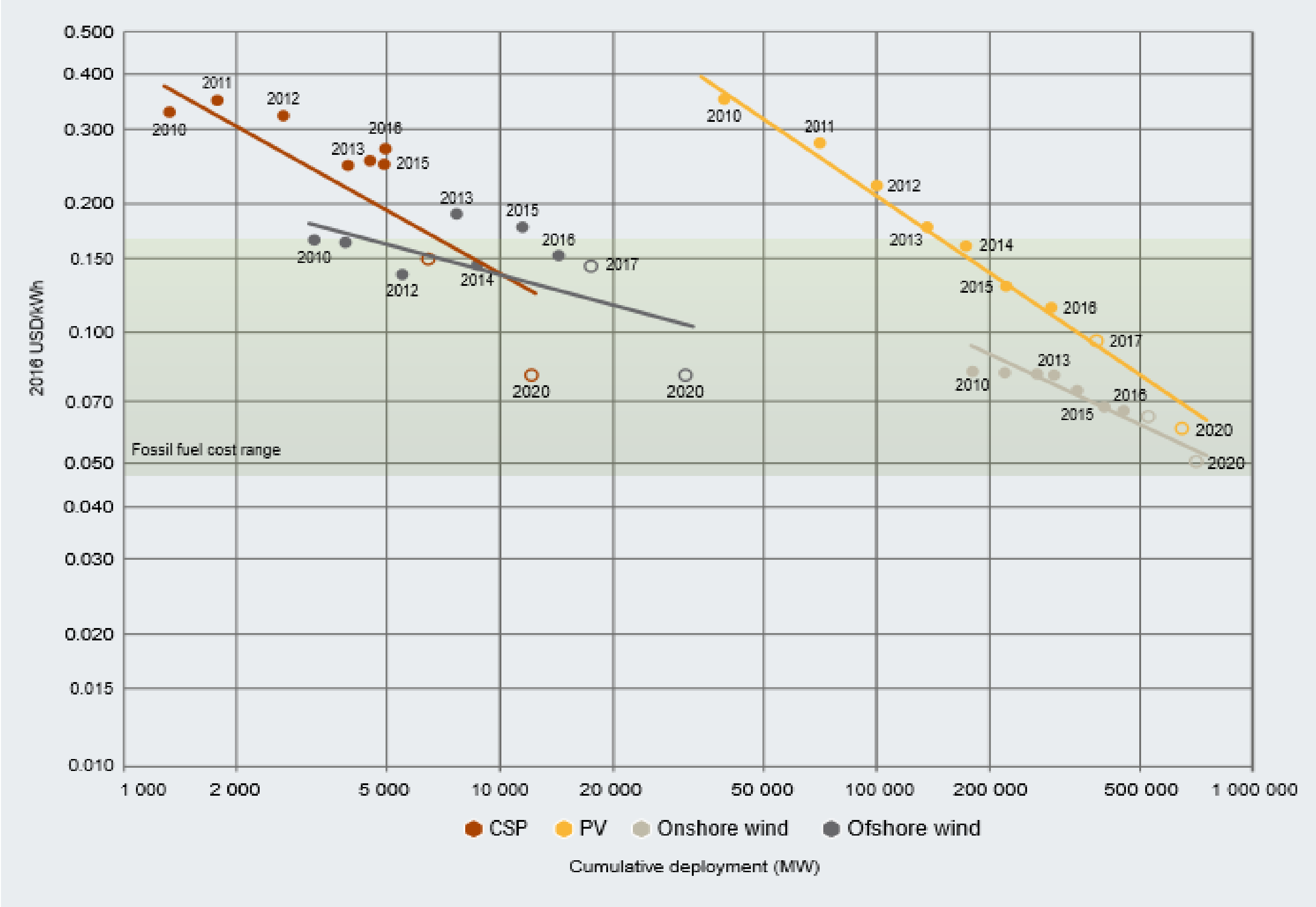
- Energy savings provides a competitive advantage
- New markets, new companies can rise
- Urban planning in a new way
- The sense of ownership versus fullfillment of a need
- Societal changes are needed
- Knowledge easily transferable and globalised
- Local production of goods is fostered with energy costs on the rise

Clean Tech Path



Renewable Energy became competitive with fossil fuel





Based on IRENA Renewable Cost Database and Auctions Database; GWEC, 2017; WindEurope, 2017; MAKE Consulting, 2017a; and SolarPower Europe, 2017a.

Storage increases capacity factor

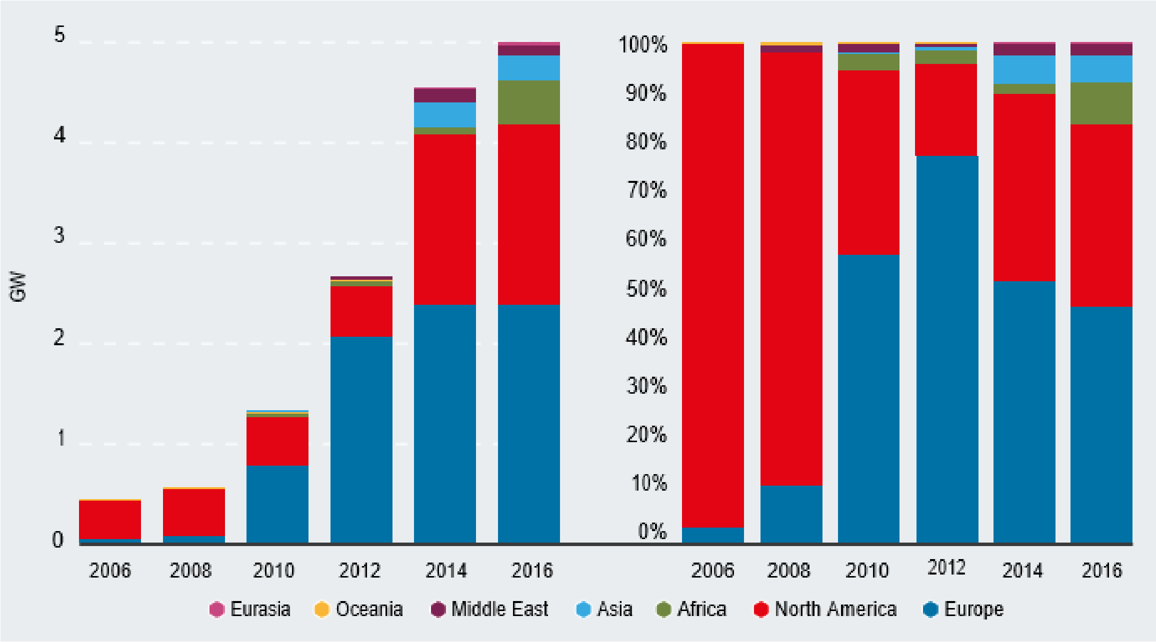
CSP has a high efficiency storage (96%) which allows dispatchability and increase system value

Storage Technology	CAPEX / kWh of capacity	
Rock Bed concepts	15 to 25 Eur / kWh_th	storasol.eu
Molten Salt	25 to 70 Eur / kWh_th	uevora.newsol.pt
Lithium-Ion battery	1400 Eur / kWh_el [0,39MEur for 0,28MWh]	bves.de
Lithium-Ion battery (Demo project)	833 Eur / kWh_el [100MEur for 120MWh]	dlr.de

The cost in Euro/kWh also depends on the storage temperature, for the same initial capital expenditures.
Using molten salts, storing heat at 565 °C doubles the storage capacity compared to heat at 400 °C, which means that the costs Euro/kWh will be cut in half

CSP Plants

- Tower Type
- Parabolic Through
- Fresnel
- Dish

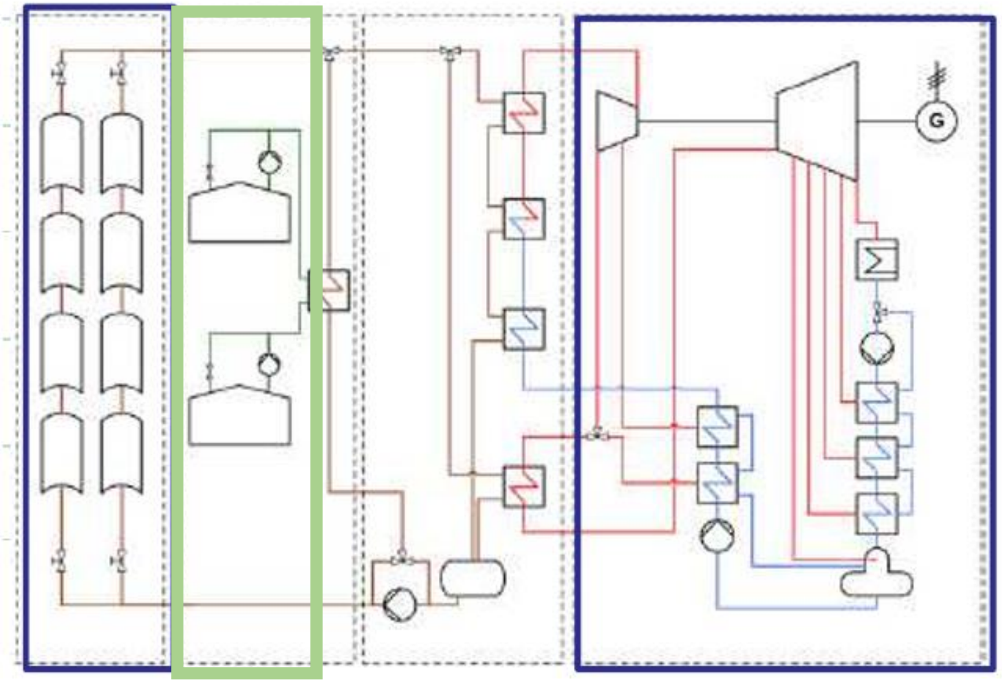


Source: IRENA, 2017a.

	Parabolic Trough	Solar Tower	Linear Fresnel	Dish-Stirling
Typical capacity (MW)	10-300	10-200	10-200	0.01-0.025
Maturity technology	Commercially proven	Commercially proven	Pilot projects	Demonstration projects

Overall Plant Efficiency

$$\eta_{overall} = \eta_{optical} \cdot \eta_{thermal} \cdot \eta_{piping} \cdot \eta_{net\_PB} \cdot \eta_{aux\_SF}$$
$$= \rho_{clean} \cdot \gamma \cdot \tau_{glass} \cdot \alpha \cdot K(\theta) \cdot \eta_{shadowing} \cdot F_{fou,mirror} \cdot F_{fou,glass} \cdot F_{tracking}$$



- Direct Systems

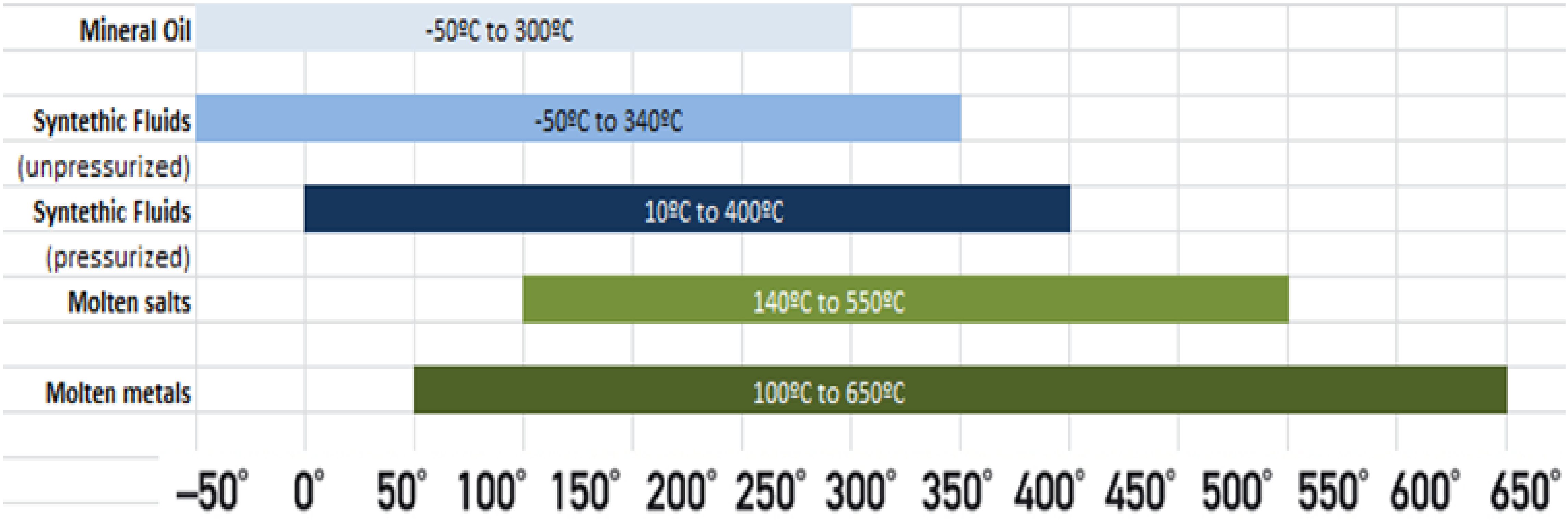
Circulating Fluid (HTF) is the Storage Fluid (HSM)

- Indirect Systems

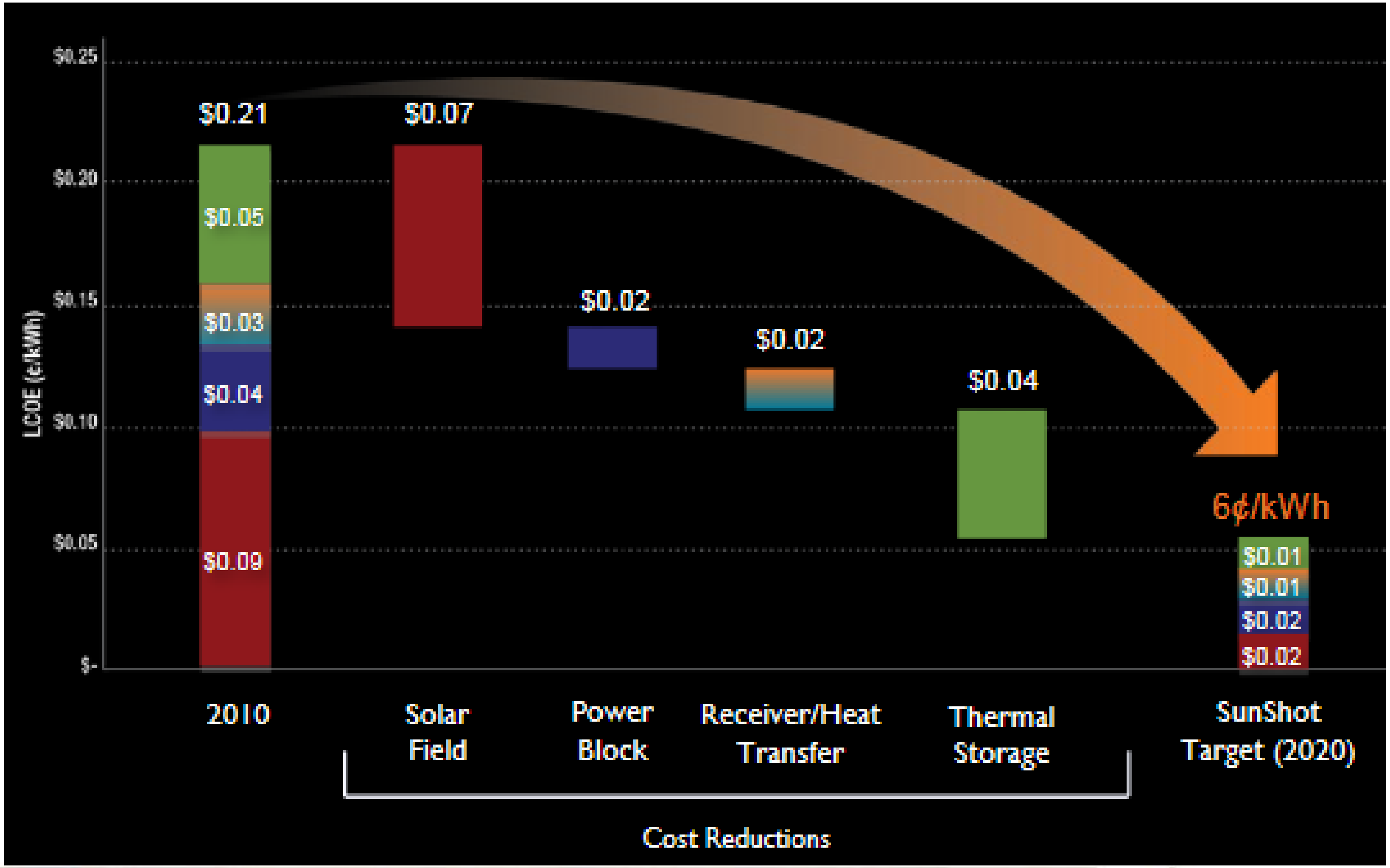
Circulating Fluid is not the Storage Fluid

CSP Plants

HTF (heat transfer fluid)



CSP Plants



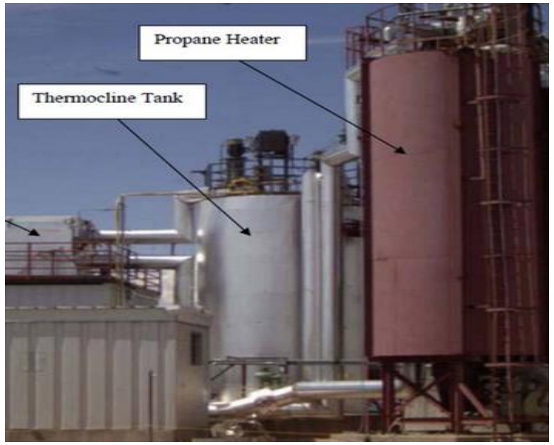
R&D driver: cost reduction

Source: SunShot (2012)

Thermal Energy Storage, State of the Art (SoA)

SoA
TES plants

HTF- Heat Transfer Fluid	HSM- Heat Storage Medium	T (ºC)
Oil	Molten salts / Ruths steam / concrete	<400ºC



HTF- Heat Transfer Fluid	HSM- Heat Storage Medium	T (ºC)
Molten salts / Steam	Molten salts / solids / PCM	565ºC

- ✓ New Design: reduce 2 tanks to 1 Thermocline Tank (w/ filler)
- ✓ New lower cost materials need to be validated up to 565ºC

R&D

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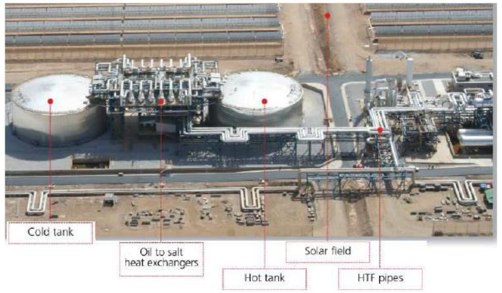
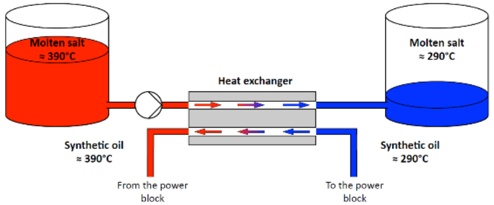
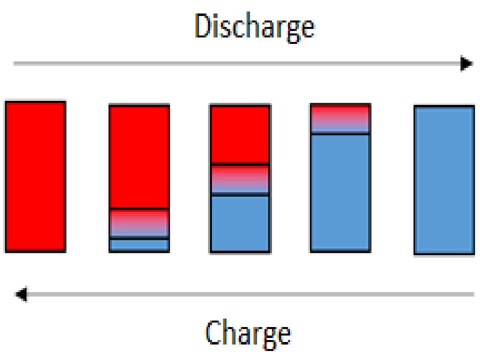
Design Concepts

Molten Salt
2 - Tank

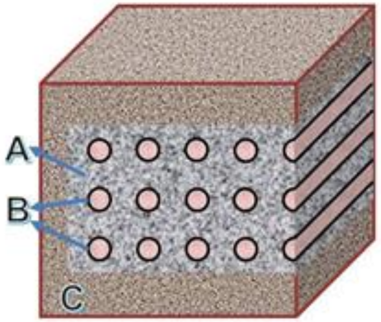


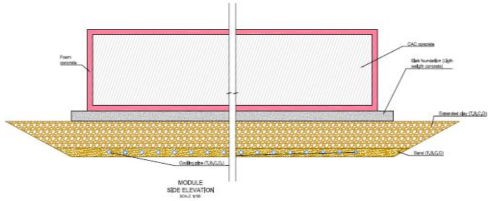


Molten Salt + Solid
1 – Thermocline tank

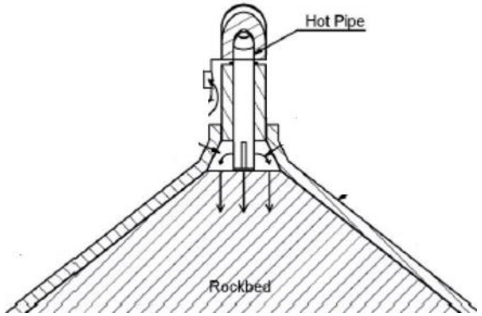


Concrete
Module





Solid rocks / slag
Bed Rock unit



Source: STERG, Universiteit Stellenbosch University

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Storage Materials

Materials considered for CSP storage media

Storage Medium	Sand-rock Mineral Oil	Reinforced Concrete	Nitrate salts	Carbonate salts	Liquid sodium
Temp. (cold) (°C)	200	200	265	450	270
Temp. (hot) (°C)	300	400	565	850	530
Avg. density (kg/m^3)	1700	2200	1870	2100	850
Avg. thermal conductivity (W/m K)	1.0	1.5	0.52	2.0	71.0
Avg. heat capacity (kJ/kg K)	1.30	0.85	1.6	1.8	1.3
Volume specific heat capacity (kWh/m^3)	60	100	250	430	80
Cost per kWh (US$/kWh)	4.2	1.0	3.7	11.0	21.0

Storage Materials

Heat Transfer Fluid = Heat Storage Media?

Name	Type	Min HTF Temp °C	Max Operating Temp °C	Freeze Point °C
Chloride Salts (50% NaCl 50% KCl)	Chloride salts	680	950	658
Solar Salts	Nitrate salts	260	600	220
Caloria	Mineral hydrocarbon oil	-20	300	-40
Hitec XL	Nitrate salts	150	500	120
Therminol VP-1	Mixture of biphenyl and diphenyl oxide	50	400	12
Hitec (60% $NaNo_3$ 40% KNO_3)	Nitrate salts	175	500	140
Dowtherm Q	Synthetic oil	-30	330	-50
Dowtherm RP	Synthetic oil	-20	350	-40

Component	Cost ($ kg^{-1})
Therminol VP-1	7.6
Hitec	1.7
$LiNO_3$	6.4
$CsNO_3$	48.0
$NaNO_3$	0.5
KNO_3	0.8
$NaNO_2$	0.45
NaCl	0.1
KCl	0.4

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Molten Salts

- Binary Mixtures

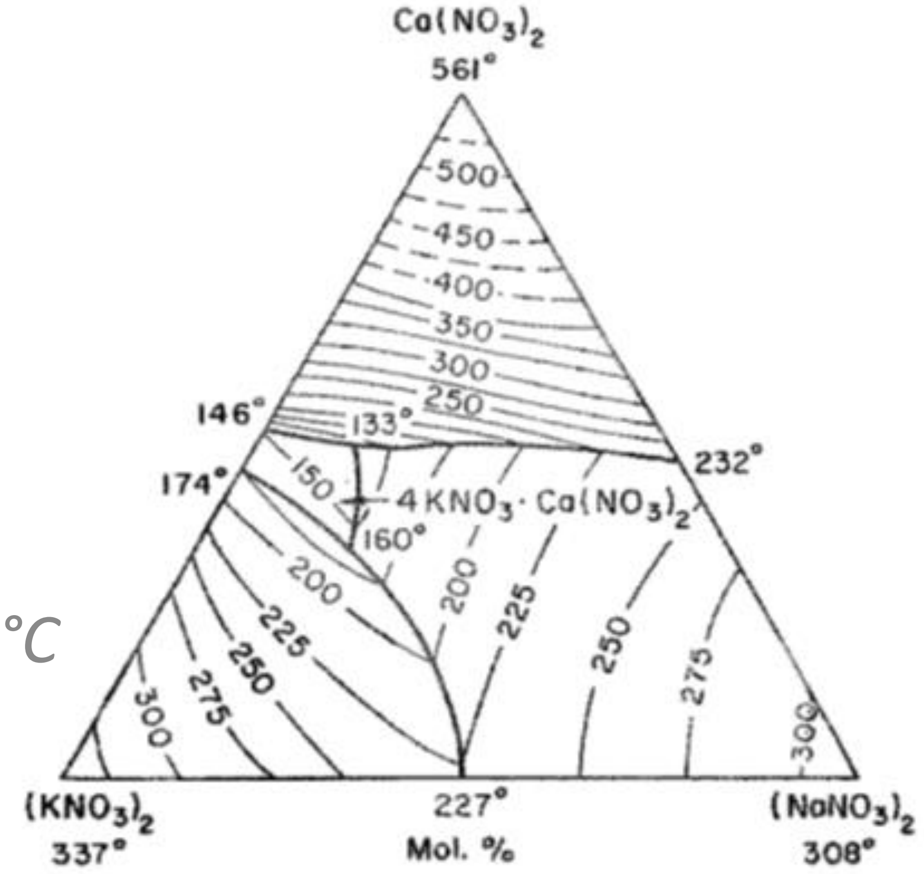
$NaNO_3$ | KNO_3

- Ternary Mixtures (Ca up to 40 wt%) Tm ~ 140°C

$NaNO_3$ | KNO_3 | $Ca(NO_3)_2$

- Quaternary Mixtures (Li up to 30 wt%) *Tm ~ 100°C*

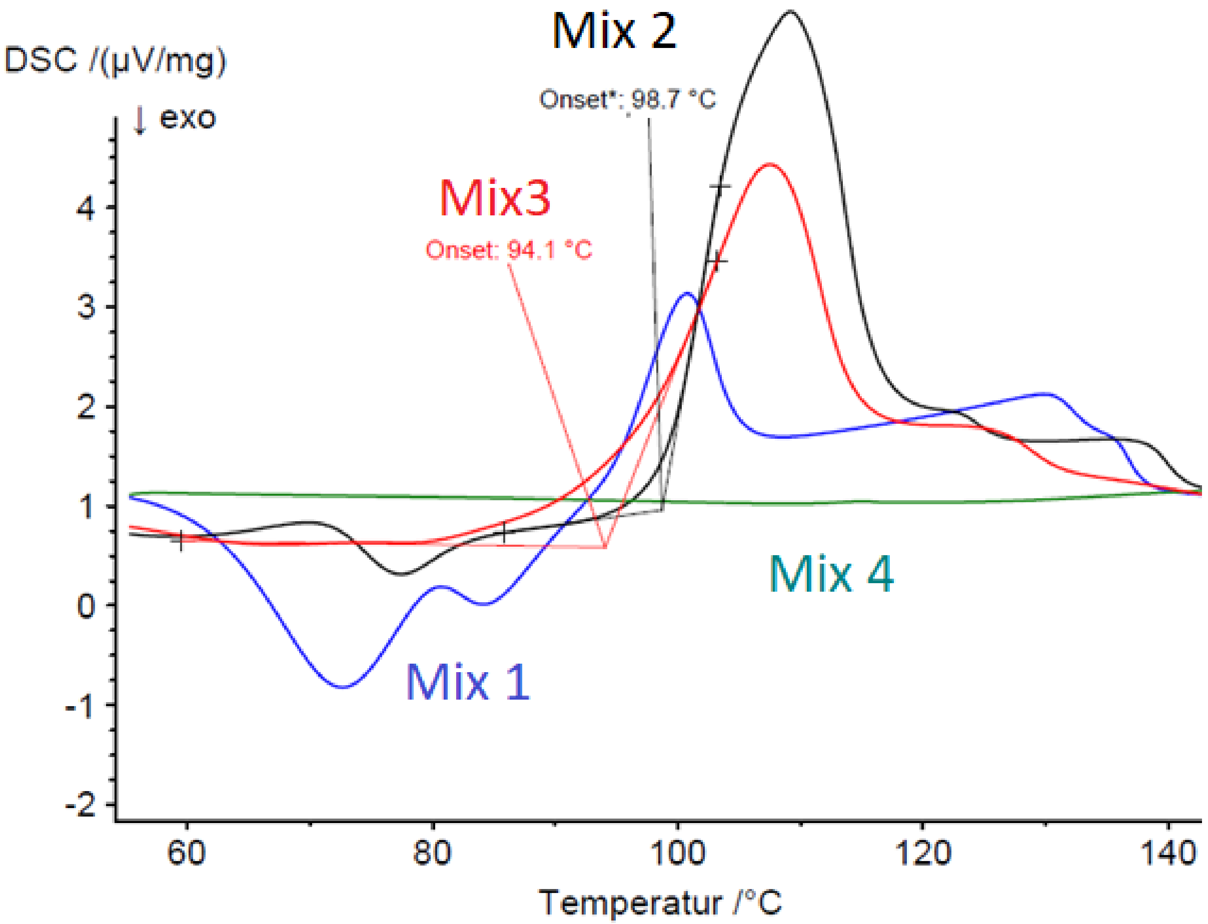
$NaNO_3$ | KNO_3 | $Ca(NO_3)_2$ | **Li NO3**



Molten Salts

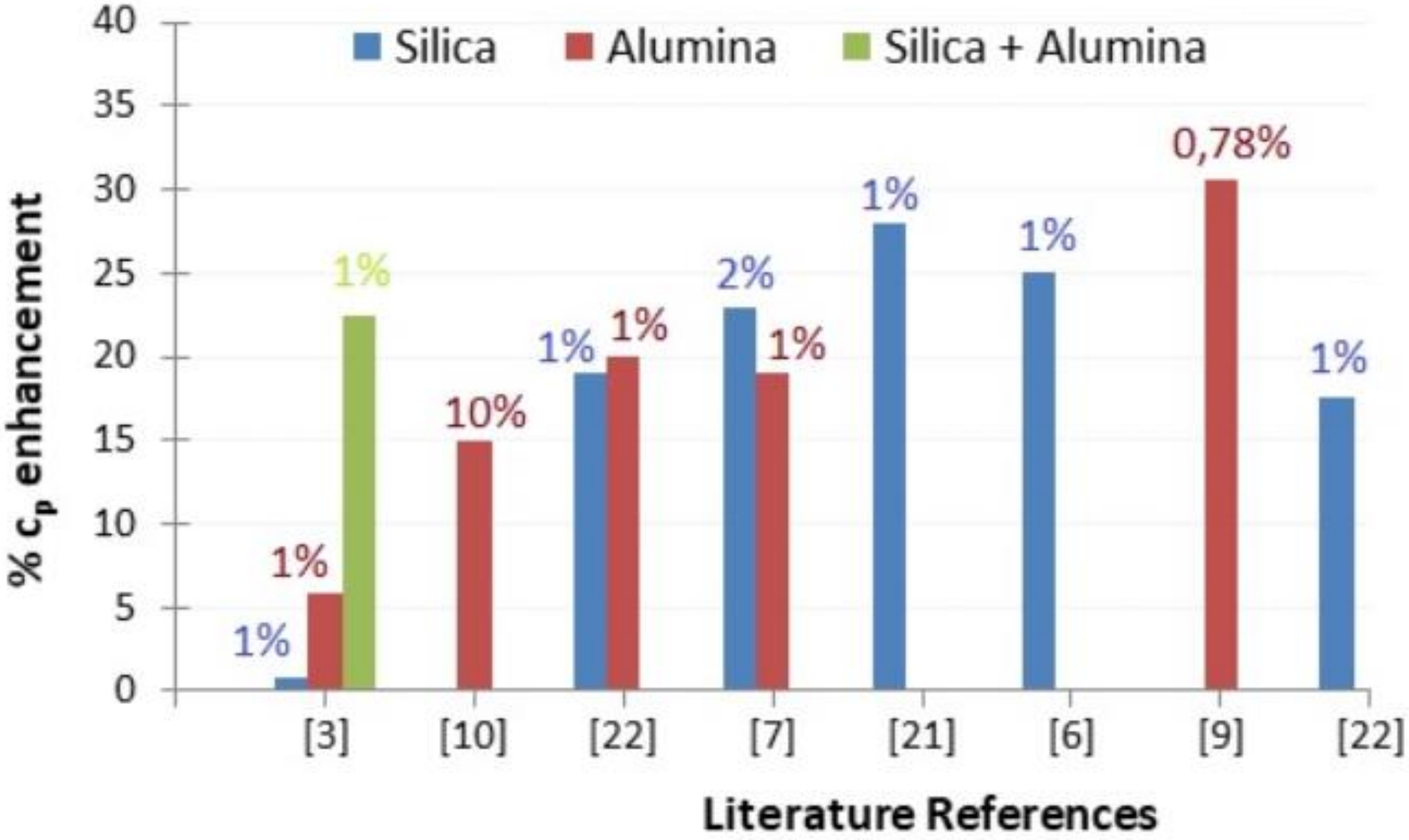
- Molten Salts: several mixtures being studied
- Aim: Reduce fusion point
- Good thermal stability for operative range

Mix	$Ca(NO_3)_2$ [mol%]	Liquidus Temp.[°C] (10K/min)
#1	12	~ 105°C
#2	5	< 115°C
#3	10	< 115°C
#4	15	*inconclusive*



Storage Materials

Molten Salts with nanoparticles (1-2%) incorporated, currently a R&D topic



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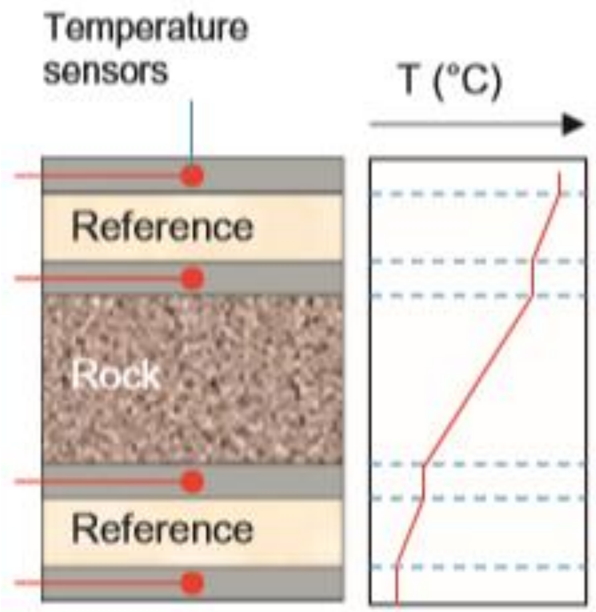
Storage Materials

Solid Materials challenge: measuring thermal properties at high temperature

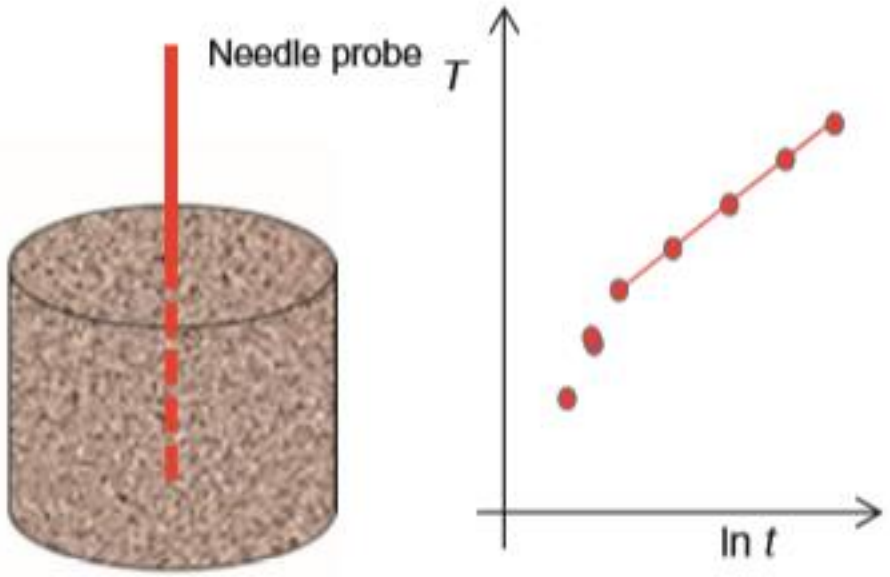
- Divided bar (steady state)

Temperature drop



- Needle (transient)

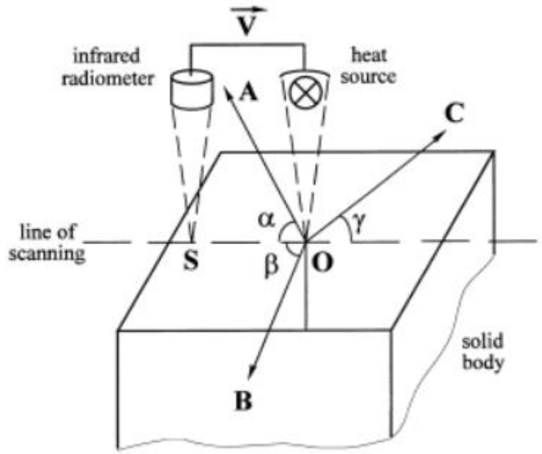
Temperature as function of time



- Optical scanning

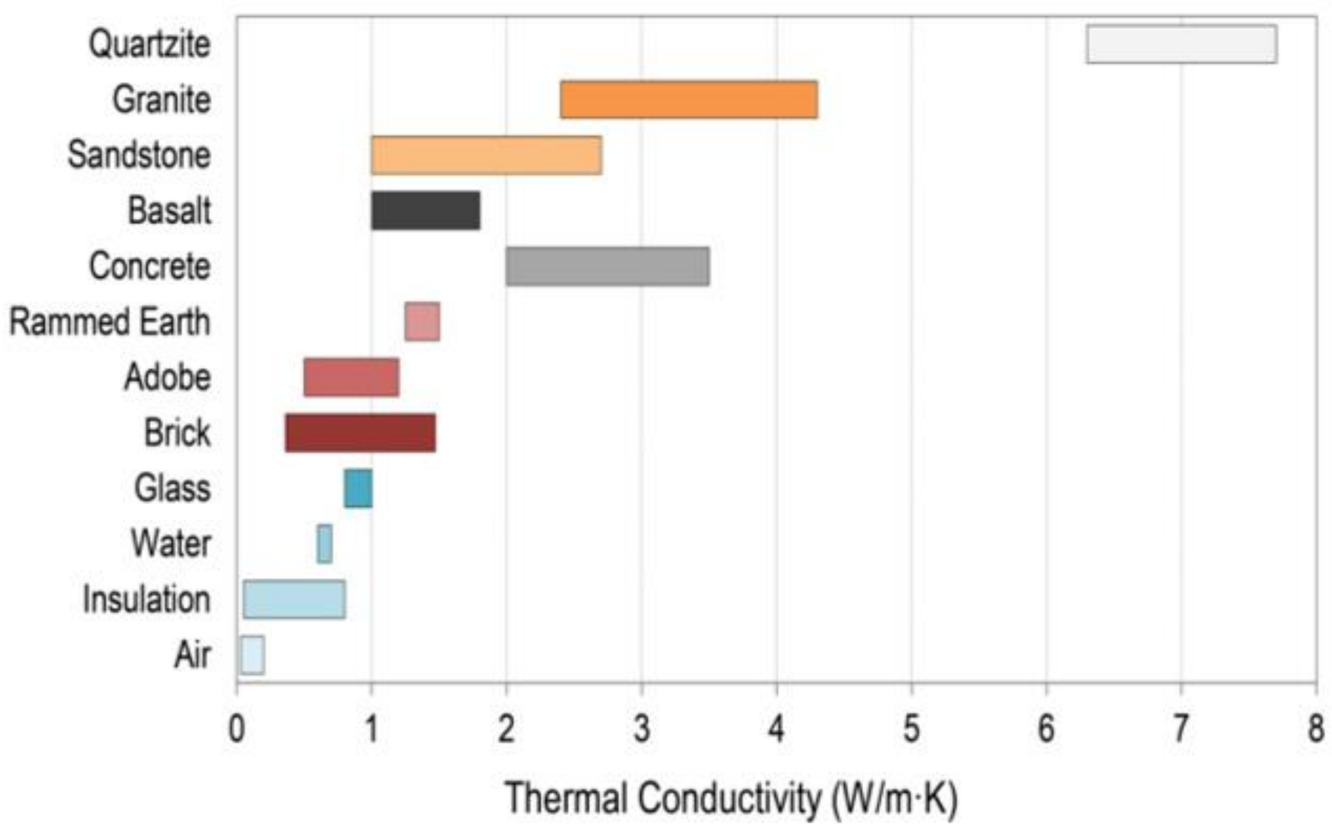
(constant heat source)

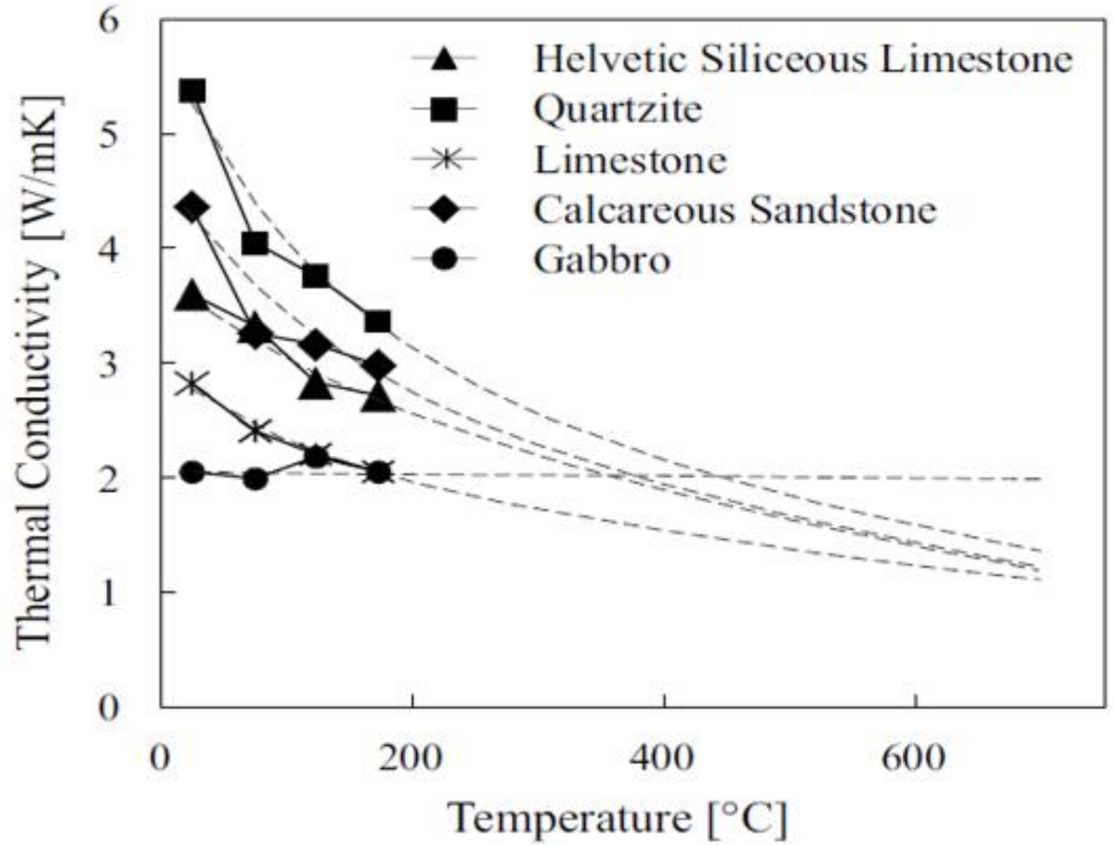
Temperature rise



Source: Sauer, 2017

Solid Materials

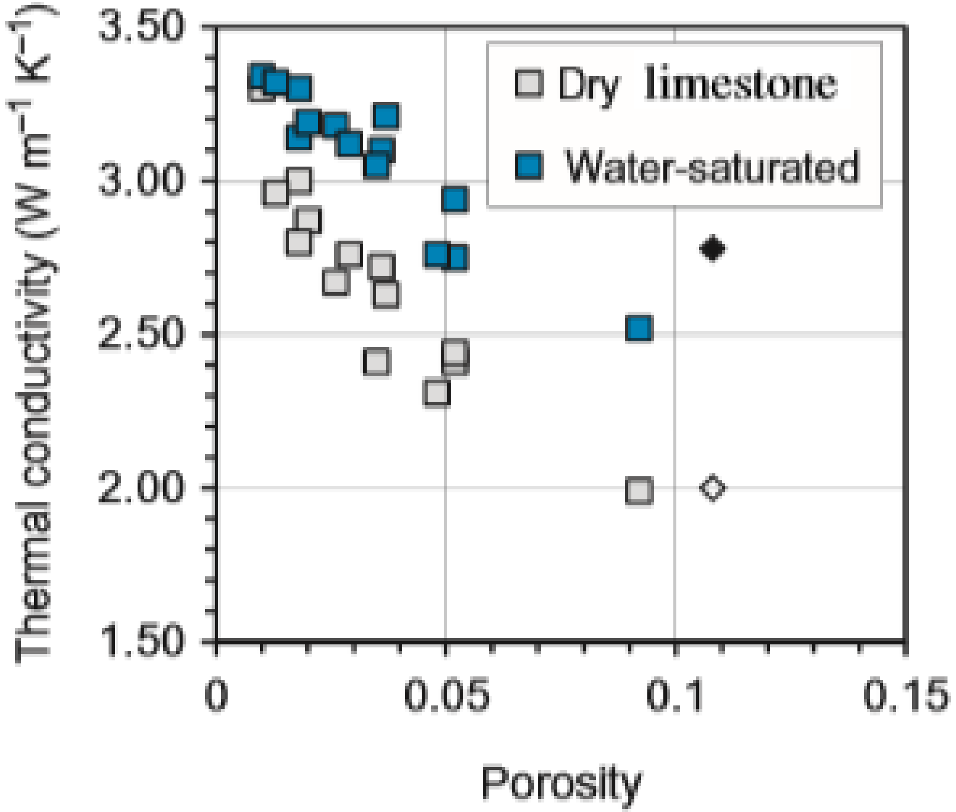


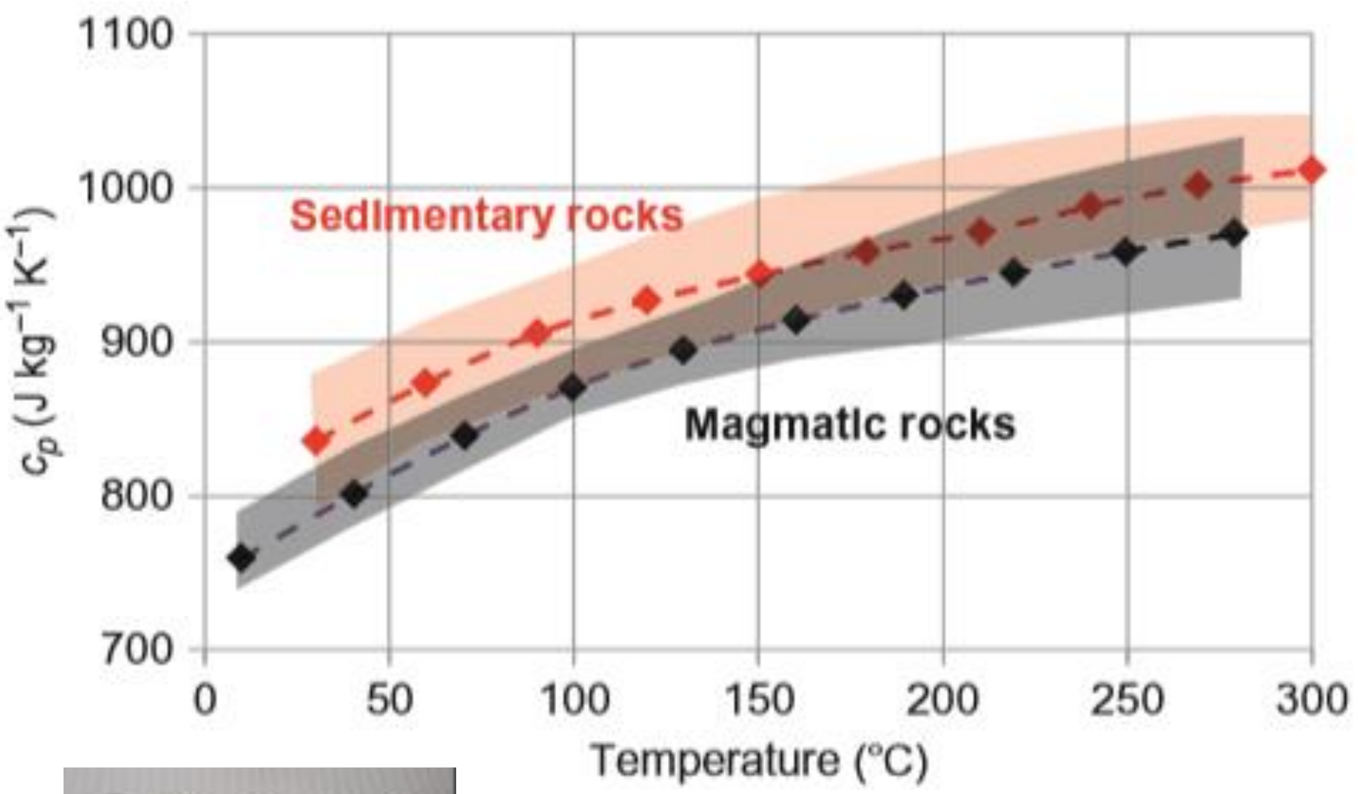


Source: Horai 1979

Storage Materials

Solid Materials





- Slag Material (São Domingos Mine)

Source: Schön 2014

R&D Storage Materials

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Molten Salts in contact with Filler Material (validation ongoing)

Sample	Size (mm)	Fayalite %	Maghemite & Magnetite %	Petedunnite %
NS-1	S (2.5 <Size1 <6.3)	79.03	5.98	14.99
	M (6.3 <Size2 <12.5)	72.25	6.24	21.51

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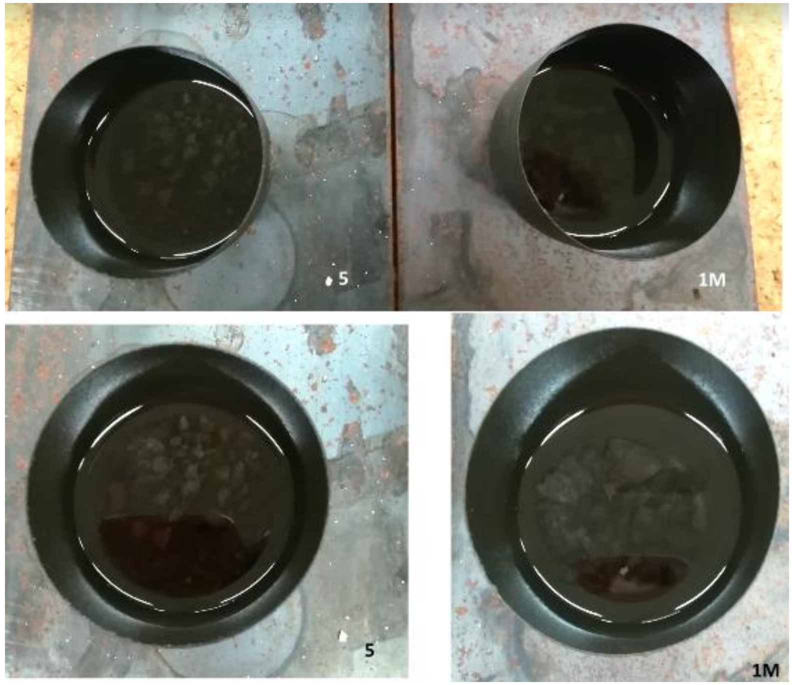
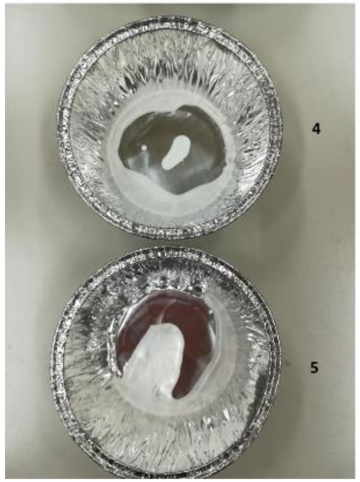
R&D Storage Materials

Interaction Solid / Molten Salts



Molten Salts post-contact Analysis

Solid Material post-contact Analysis



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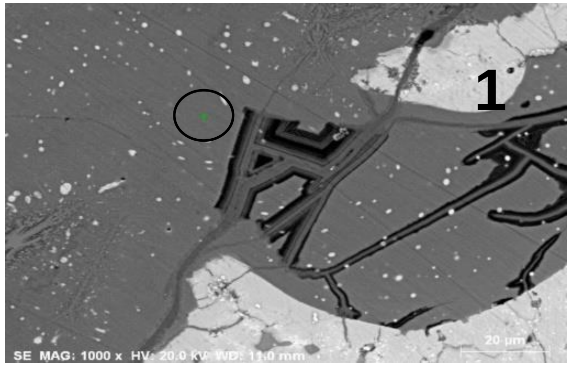
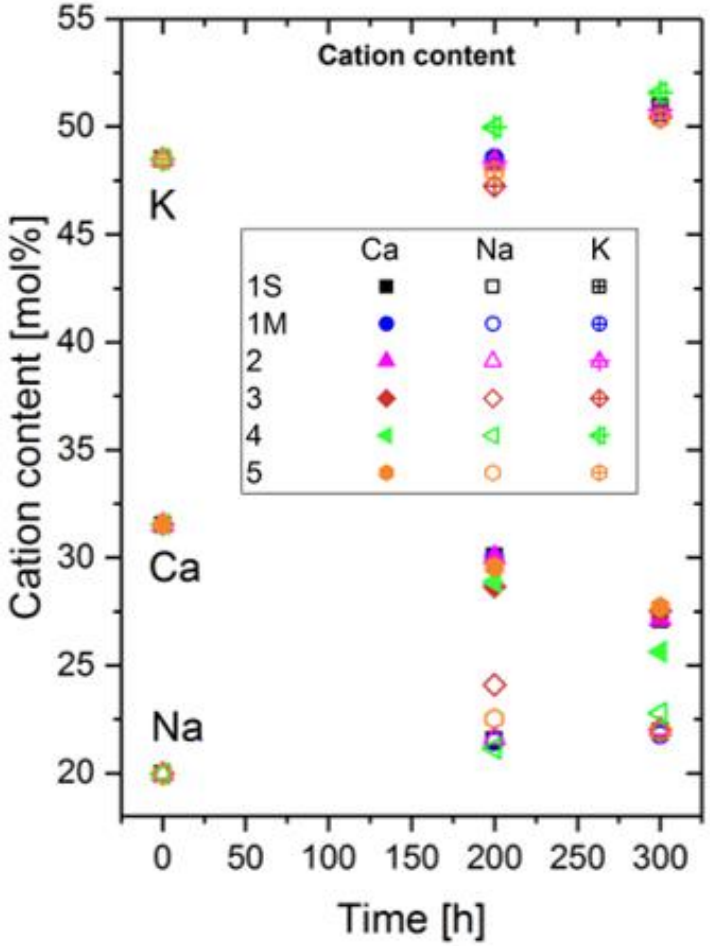
R&D Storage Materials

Solid material analysis



Molten Salts analysis

Chemical decomposition is checked for molten salt mixture validation



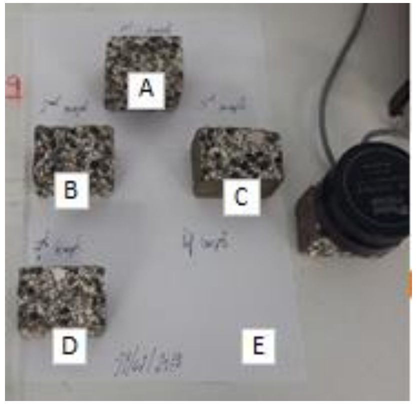
Solid Material + Ternary Molten Salt					
Sample	Size	Weight Crucible [g]	Total Weight [g]	Initial weight solid [g]	Final weight solid [g]
NS-1	S (2.5 <Size1 <6.3)	42.1	150.20	35.03	34.02
	M (6.3 <Size2 <12.5)	49.9	149.91	35.23	34.27

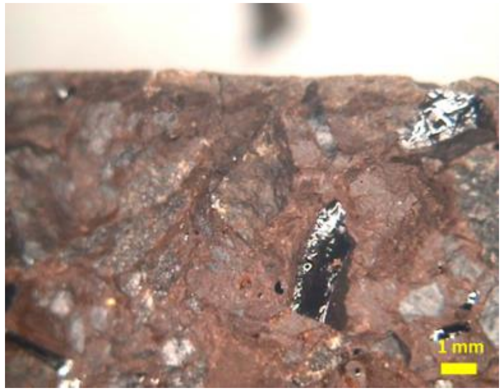
R&D Storage Materials: New Binder

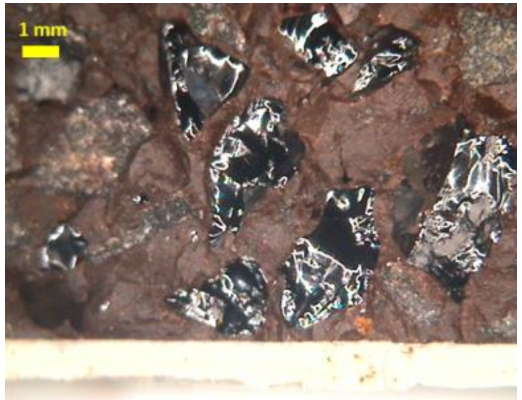
NEWSOL

- Improve Thermal properties
- Special cement as a binder
- Slag as aggregate

Coated and Uncoated samples – up to 1500 hours in contact with MS







➢ A new binder requires termal optimization and durability validation under termal cycles

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R&D Storage Materials: New Insulation

Foam Concrete is being optimized in terms of its density and amount of additive

- High Temp. Concrete = 2000 kg /m3; 2,0 W/mK
- Foam Concrete = 250 – 400 kg /m3; 0,05 – 0,10 W/mK

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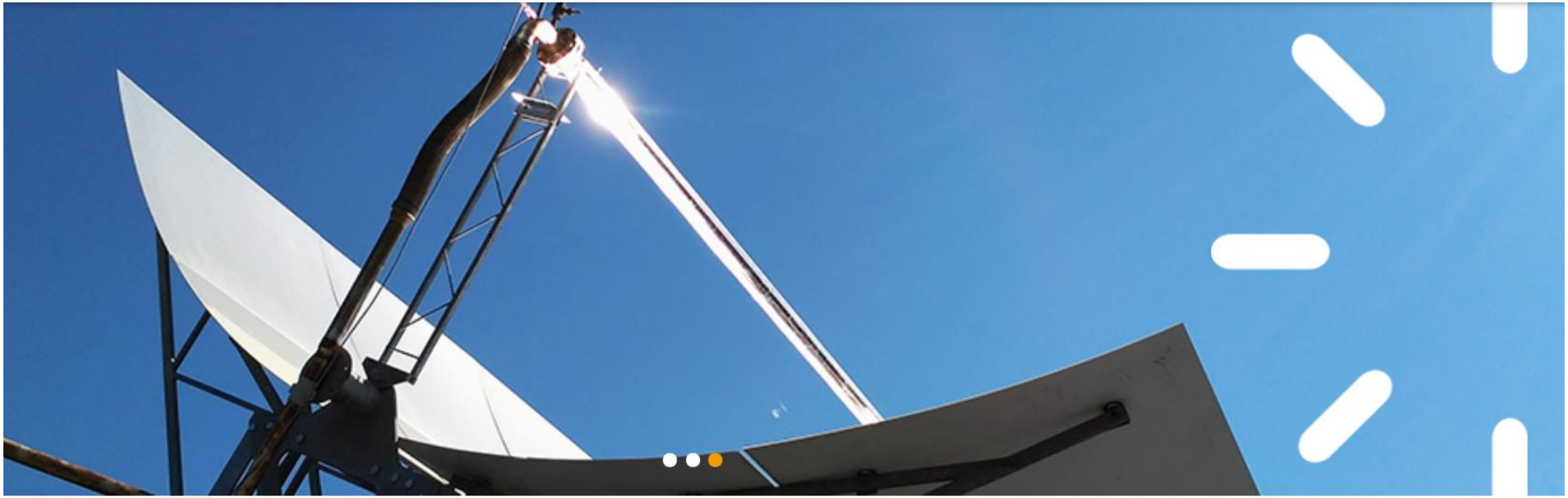

NEWSOL project addresses the specific challenge towards high efficiency solar energy harvesting by advanced materials solutions and architectures that are in line with those specified in SET-plan.

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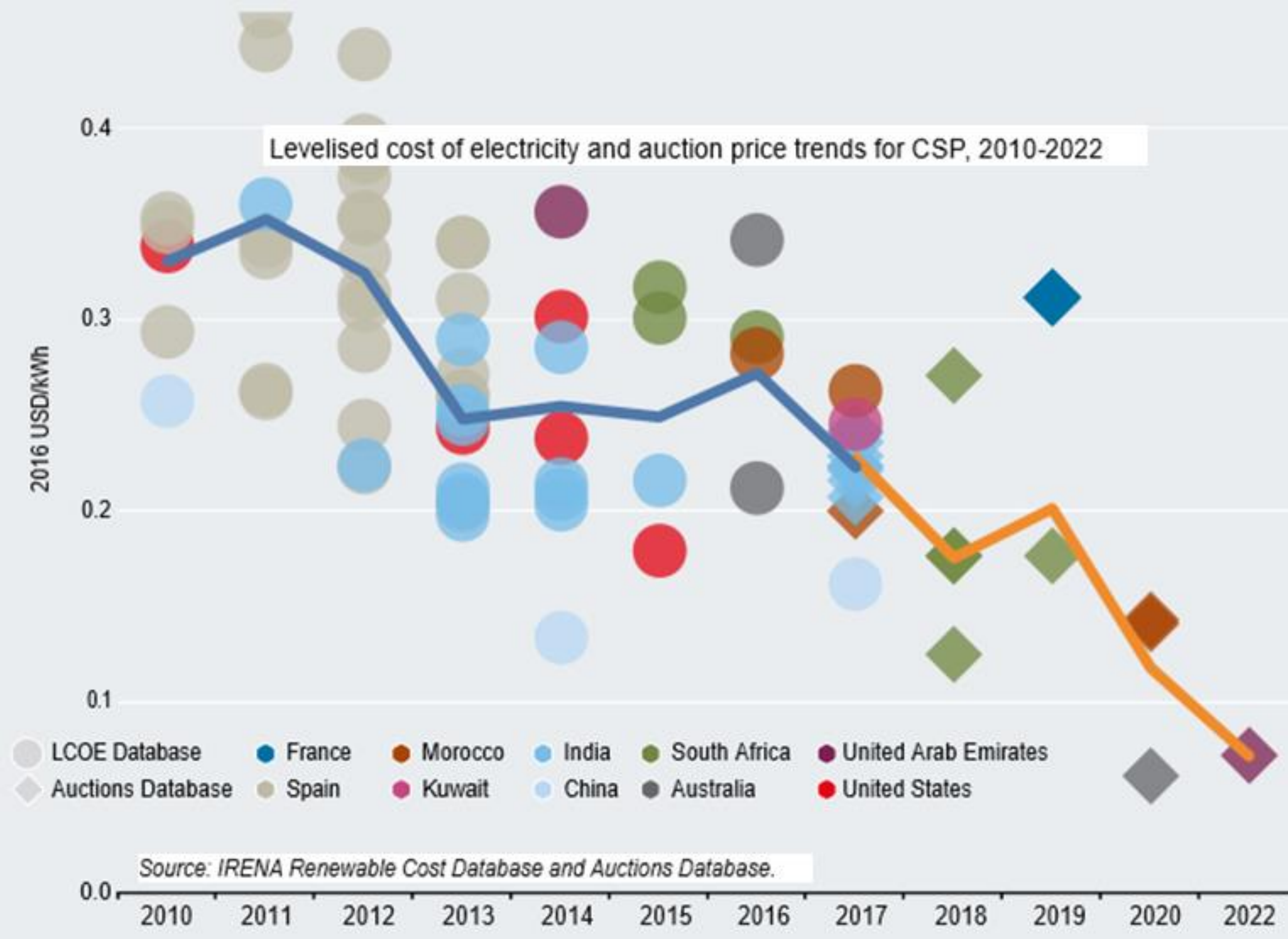
Future Perspectives

- 1st step (2018): Validating the Molten Salt mixtures at Lab scale
- 2nd step (2019): Validate at EMSP – Evora Molten Salt Platform (1,6 MWth)

Future Perspectives



Strategic Partnerships

- DLR – German Aerospace Center, Germany

R&D area: Solar Field Testing / Operation

Deutsches Zentrum für Luft- und Raumfahrt

- University of Stellenbosch, South Africa

R&D area: Rock bed concepts

STERG — Universiteit Stellenbosch University

- Universidad de Antofagasta, Chile

R&D area: Molten salt mixtures

UA Universidad de Antofagasta

Conclusion

- ✓ Energy Transition is a must, societies that achieve closed loop, long term sustainable solutions will be better of in the future
- ✓ Technology is just a part of the challenge. Societal changes are also very important
- ✓ Renewable Energy systems are local dependent, and have been gaining momentum via LCOE cost reduction of CSP Plants with Energy Storage
- ✓ Design concepts at R&D level can bring costs further down
- ✓ R&D on Storage Materials is a critical issue for success
- ✓ Let's have also a sunny future in Chile


Thank you!
Muchas Gracias!
Luís Guerreiro, PhD, MBA, lguerreiro@uevora.pt